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# **SMART MATERIALS AND STRUCTURES DEMONSTRATIONS**

## **SMART ROTORS**

**BOEING, MIT, UCLA, UM**

**DARPA Smart Structures and Actuators  
Technology Interchange Meeting #7**

**June 26-28, 2000**

**Friedrich Straub  
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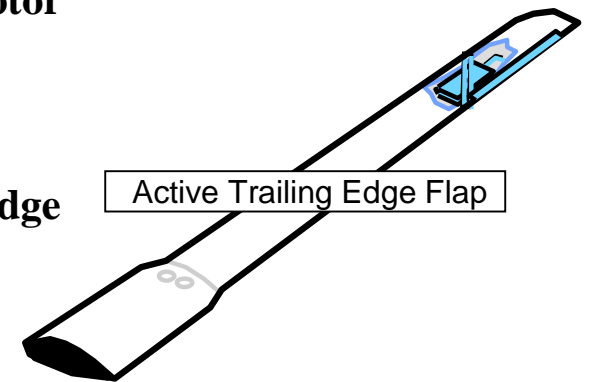
## SMART ROTOR -- OBJECTIVES

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- Demonstrate smart materials for active control on helicopter rotor
- Improve rotor and vehicle performance

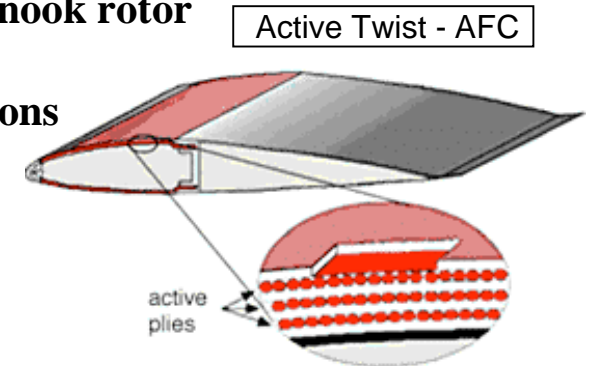
### Task 1: MD900 active flap flight test

- Design, build and flight test MD900 rotor blades with trailing edge flap, driven by piezoelectric actuator
- Demonstrate vibration, aerodynamic performance, and noise benefits; assess cost benefit



### Task 2: Active material rotor

- Design, build and hover test a scaled model of an advanced Chinook rotor using piezo active fiber composites (AFC) for blade twist
- Initiate the process for qualifying AFCs for aerospace applications



### Expected Results:

- Improved component lives, reduced maintenance
- Improved crew/passenger/community acceptance
- Improved range, maneuverability

### Future:

- Smart material active control for enhanced AH-64, V-22, CH-47, FTR, RAH-66
- Primary flight control via smart materials actuation

## SMART ROTOR -- SCHEDULE

MD900 active flap rotor flight test - Schedule																
	1998				1999				2000				2001			
Task	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Actuation system development, component tests																
Blade, flap, actuator design integration, component tests																
Fabrication																
Integrated system test																
Whirl tower test																
MD900 flight test																



Active Material Rotor - Schedule																
	1998				1999				2000				2001			
Task	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Experimental Correlation/Calibration																
Pre-Design																
Active Ply Characterization																
Detail Design & Fabrication																
Hover Test																

# SMART ROTOR -- TEAM

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## Task 1

- **Boeing:** - design and fabricate rotor, blade, flap, piezo actuator, power amplifier ⇨
  - system integration, whirl, flight test ⇩
- **MIT:** - 1/6 scale CH-47 active flap rotor fabrication and spin test ↑
  - design x-frame actuator for MD900 ↑
  - develop closed loop control algorithm (continuous time methods) ⇨
- **UCLA:** - test piezoelectric materials and stacks ⇨
  - electro-thermo-mechanical properties and fatigue ⇨
- **UM:** - develop rotor/flap/actuator aeroelastic models; perform simulations ⇨
  - develop closed loop control algorithms (neural network) ⇨
  - wind tunnel test of model scale active flap rotor ⇨
  - stack performance tests, actuator spin tests ↑

## Task 2

- **Boeing:** - requirements, rotor system design, testing and interpretation ⇨
  - electronics design, fabrication, and integration ⇨
- **MIT :** - material characterizations, risk reduction testing ⇨

## Other Support and Interactions

- **PI, RSC, TRS** - supply piezoelectric stacks; **C3** - supply AFCs
- **DARPA** funded - ACT, AFCC
- **NASA Langley** ATR program

# SMART ROTOR -- 99/00 ACOMPLISHMENTS

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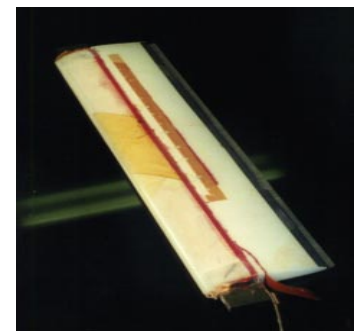
## Task 1

- **Completed piezo actuator development**
  - 15% growth, high voltage stacks
- **Completed blade/actuator design integration, component tests**
- **Tested custom piezo stacks - performance, temperature, and fatigue**
- **Continued development of continuous time HHC and NNC algorithms**
- **Demonstrated NNC on two smart material model rotor concepts**
- **Started fabrication of first article blade, flap, actuator**
  - Tool proof, to be used for integrated system test



## Task 2

- **Completed Risk Reduction Testing**
  - Designed, fabricated and tested blade sections
- **Completed Detailed Design of the Active Materials Rotor (AMR)**
  - PDR held in December 1999, CDR in April 2000
  - Completed system level impact, and feasibility studies
- **Developed Material Qualification Plan**
  - Identified critical testing for Aerospace Approval
  - Completed key characterization testing
  - Only program investigating mechanical properties of AFCs



# SMART ROTOR -- SUMMARY

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## Task 1

- Piezo stack quality and endurance remain key issue; PI - quality, RSC - performance
- Growth actuator with high voltage stack exceeds requirements (projected 3 deg w RSC)
- Blade design integration challenges overcome; required design changes incorporated
- Started fabrication of full scale hardware; good interaction w production shop
- Continuous time HHC and NNC offer improved performance vs basic HHC
- Demonstrated NNC on active flap rotor in hover and forward flight; flapping, thrust

## Task 2

- We completed design and are now building an advanced geometry active materials rotor (of interest to Boeing and the Army) whose results will be directly applicable for and transitioned to full-scale in 2003-2004.
- On track to complete hover test demonstration in 2000

## Follow-on Programs

- SIFT: smart in-flight tracking system, using SMA actuator -- NRTC
- SEW-B - Structurally embedded Wirebus - NRTC
- VGART/D: variable geometry adv. rotor technology/demonstrator -- US Army

## Potential Transition

- Advanced Apache in-flight tracking -- US Army
- Block II, V-22 -- Navy/Marines
- Advanced CH-47, Future Transport Rotorcraft (FTR) -- US Army



## TASK 1: MD900 ACTIVE FLAP ROTOR FLIGHT TEST

**MIT AMSL**



Smart Structures & Actuators  
Technology Interchange Meeting  
June 26, 2000

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# SMART ROTOR PROGRAM TASK 1 -- OVERVIEW

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## Background:

- Rotorcraft design compromise; hover/forward flight and unsteady environment
- Smart material technology offers best opportunity to overcome inherent barriers

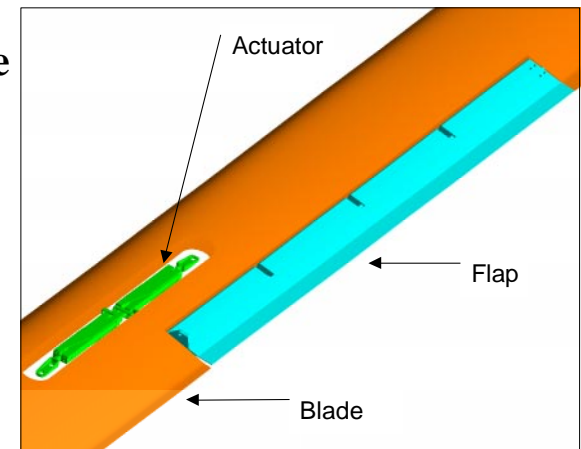
**Program:** DARPA funded, ARO monitored, 48 months Phase II

**Objective:** Demonstrate smart materials for active control on helicopter rotor

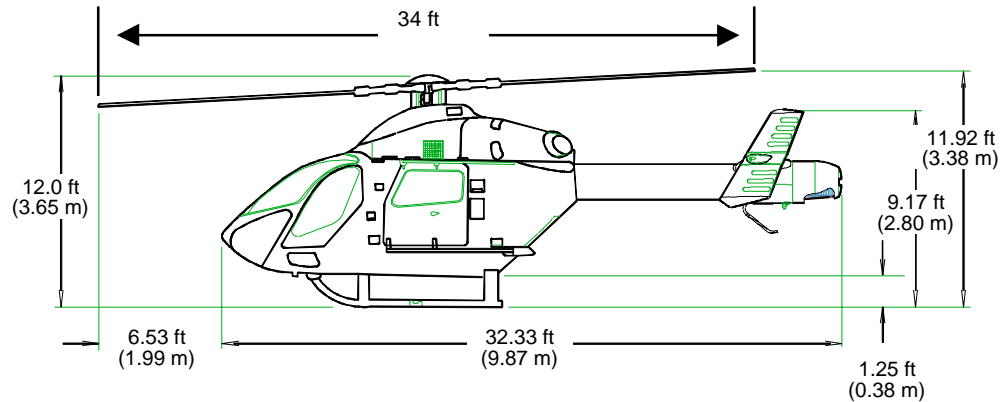
- performance and cost benefits

## Task 1 Approach:

- Select MD900 rotor; production blade design
- Trailing edge flap; improved vibration, noise, performance
- In-blade piezoelectric actuator development
  - piezo stack testing: performance, fatigue
  - power amplifier development
- Blade actuator design integration
- Smart rotor/actuator fabrication
- Control algorithms: continuous time HHC and NNC
- System integration, whirl tower, MD900 flight test

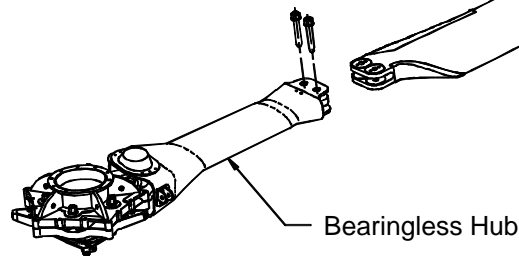


# SMART MATERIAL ACTUATED ROTOR TECHNOLOGY (SMART)



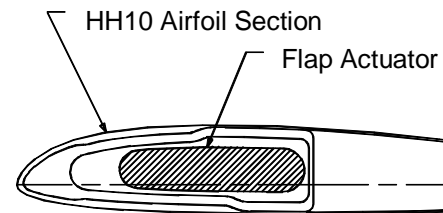
MD900 HELICOPTER

COMPOSITE BLADE ASSY



Flap Actuator

Active Control Flap,  
Noise and Vibration



BLADE CROSS-SECTION

## ACTIVE CONTROL FLAP -- GOALS

### Rotorcraft performance gains

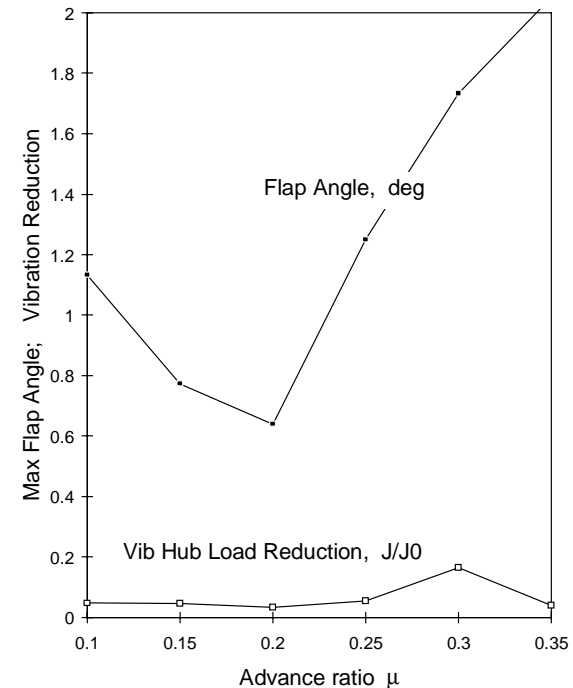
- **Vibrations: 80% reduction in airframe vibrations**
  - ride quality, component reliability and life
  - maintenance
- **Acoustics: 10dB reduction in BVI noise**
  - community acceptance, detectability
- **Aerodynamic performance:**
  - 10% gain in rotor lift/drag -- range
  - stall alleviation -- maneuverability

### System cost benefits

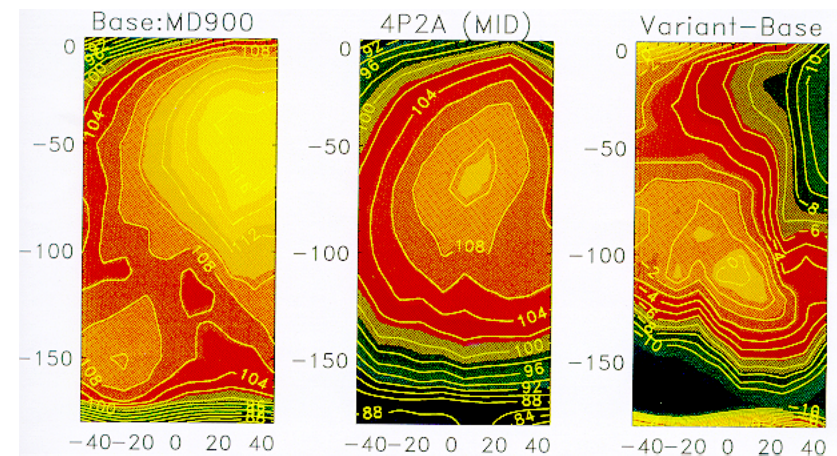
- **Reduced failure rate, maintenance**
  - life cycle cost, fleet readiness
- **Improved productivity**

### System design goals, constraints

- **Safety, simplicity, modularity**
- **Minimize actuation requirements**
- **Testbed for alternate actuators**
- **Blade structural integrity, environment**



### Vibration and Noise Reduction Simulations



$\delta f=0$

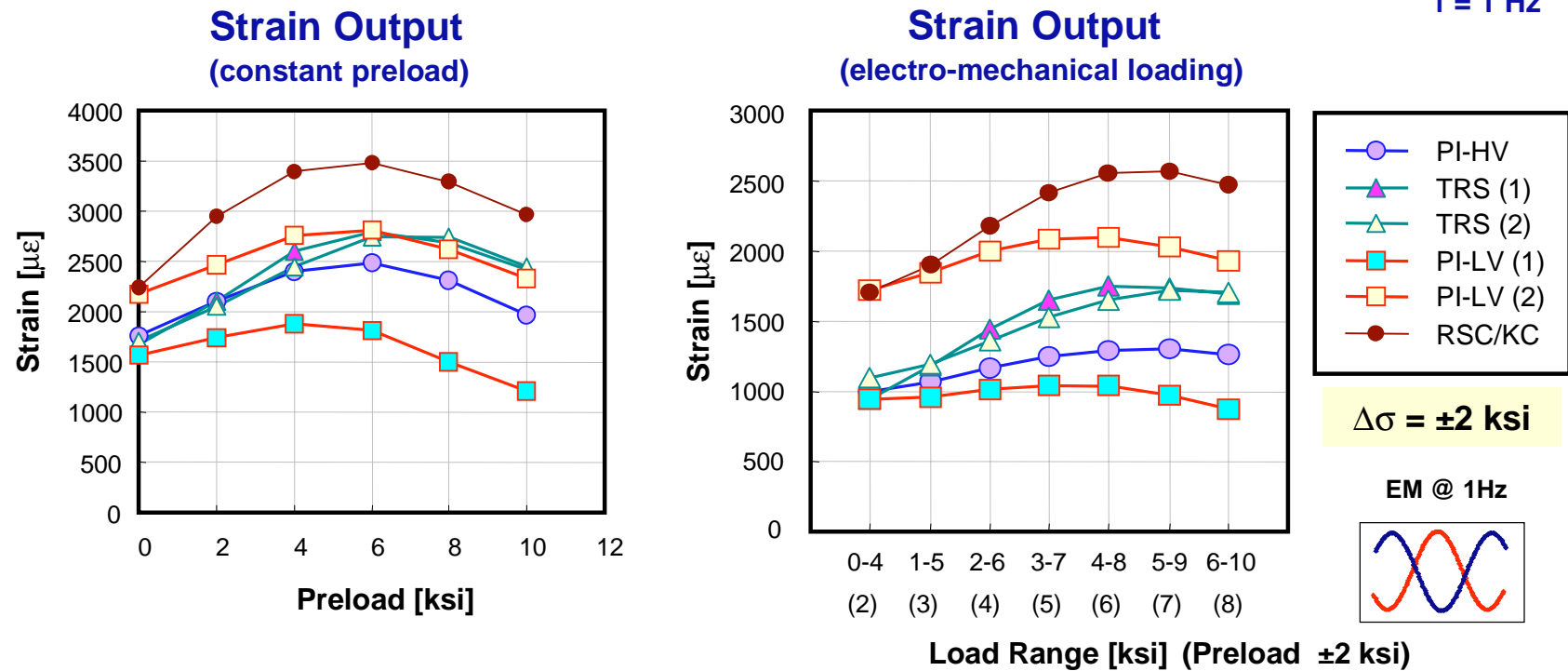
$\delta f=2\cos(4w-240)$

$\Delta=-5\text{dB}$



## Piezoelectric Stack Testing -- Comparison of Properties

f = 1 Hz

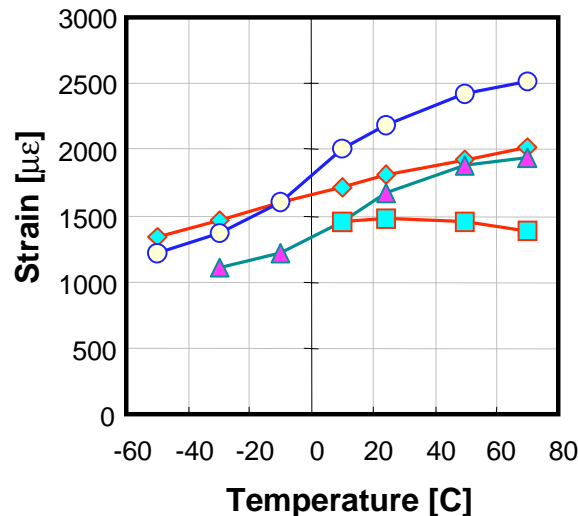


- Strain output increases with an increase in preload; optimum values at 4-6 ksi
- Highest strain output for RSC/KC stacks; >3,400  $\mu\epsilon$  at 6 ksi
- Large variation of properties as a function of applied preload
  - less dependence on load variation desirable

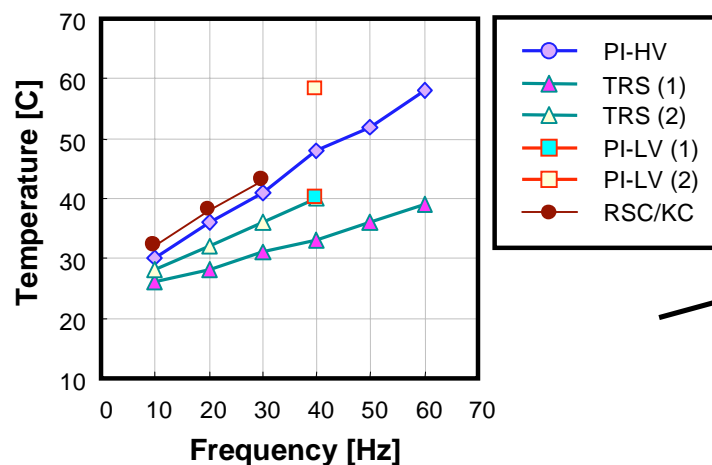
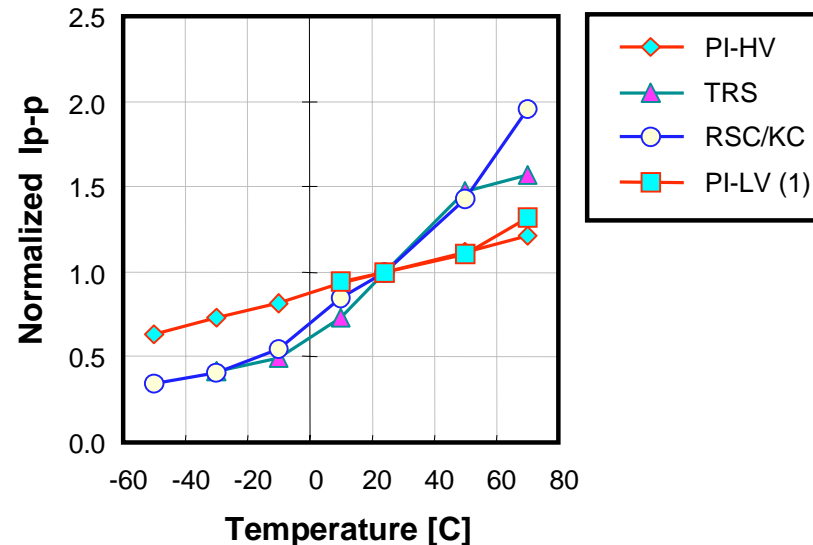
# Piezoelectric Stack Testing -- Comparison of Properties

## - Temperature Effects (no mechanical load) -

**Strain output**



**Current draw**

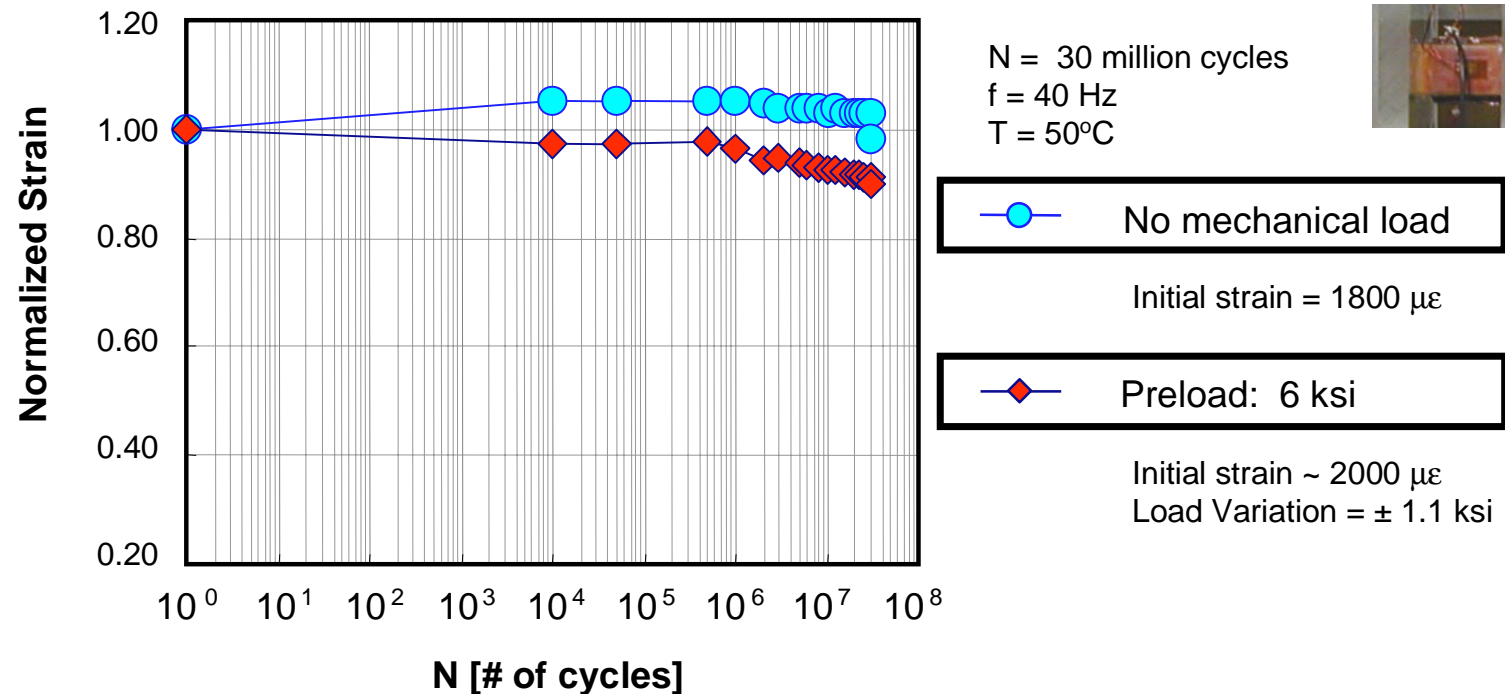


### Influence of cyclic frequency on temperature rise in fatigue (start at room T = 24 C):

- final stack's surface temperature depends on:
  - volume and surface to volume ratio
  - applied electric field
  - linear function of frequency
- temperature changes under elevated T and mechanical load need to be investigated:
  - larger dielectric losses

## Electro-Mechanical Fatigue Tests -- PI-HV Stacks

- Recommended maximum electric field: -200/1000 Volts (-0.4/2.0 MV/m)



- Degradation of properties:
  - ~10 % after 30 million cycles (200 flight hours) under preload
    - most of the degradation (6%) during first 3 million cycles
  - negligible degradation of properties under no mechanical load

## 2-X FRAME PIEZO ACTUATOR

2-x frame actuator, w stock PI LV stacks

- Bench test: low performance
- Shake, spin tests: excellent robustness

1-x frame actuator w custom RSC & TRS HV stacks

- Good performance; stack reliability issues

Grow stack dimensions by 15%; output by 52%

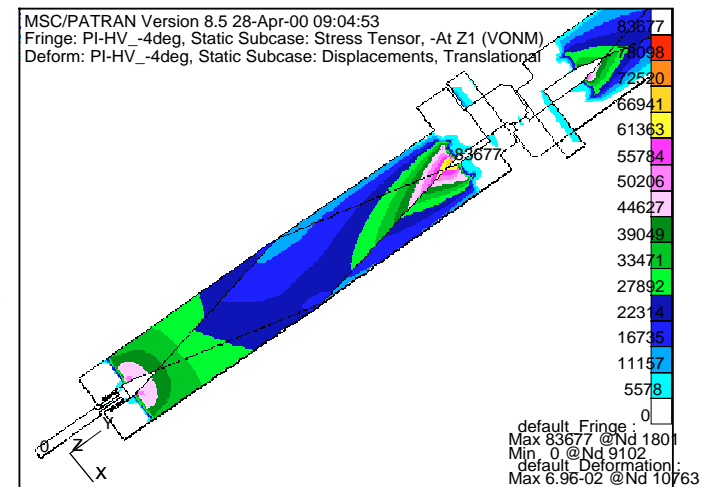
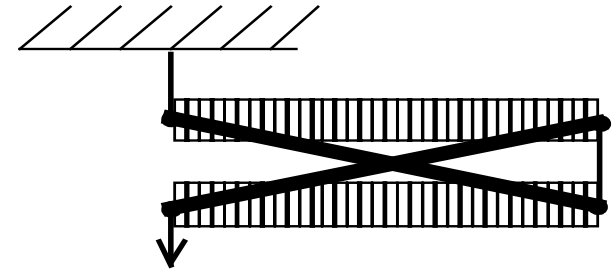
Switch to HV stacks

- Reduce stack/frame/frame clearance
- Maintain stack separation (centerline)
- Widen frame at output end
- Matched radius stack seats; low friction
- Jack screw preload adjust
- FEM structural, performance analysis
- Built 2-x SL model
- Built 1-x prototype; stiffness, strength testing
- Projected performance meets requirements

Started fabrication of tool proof actuator

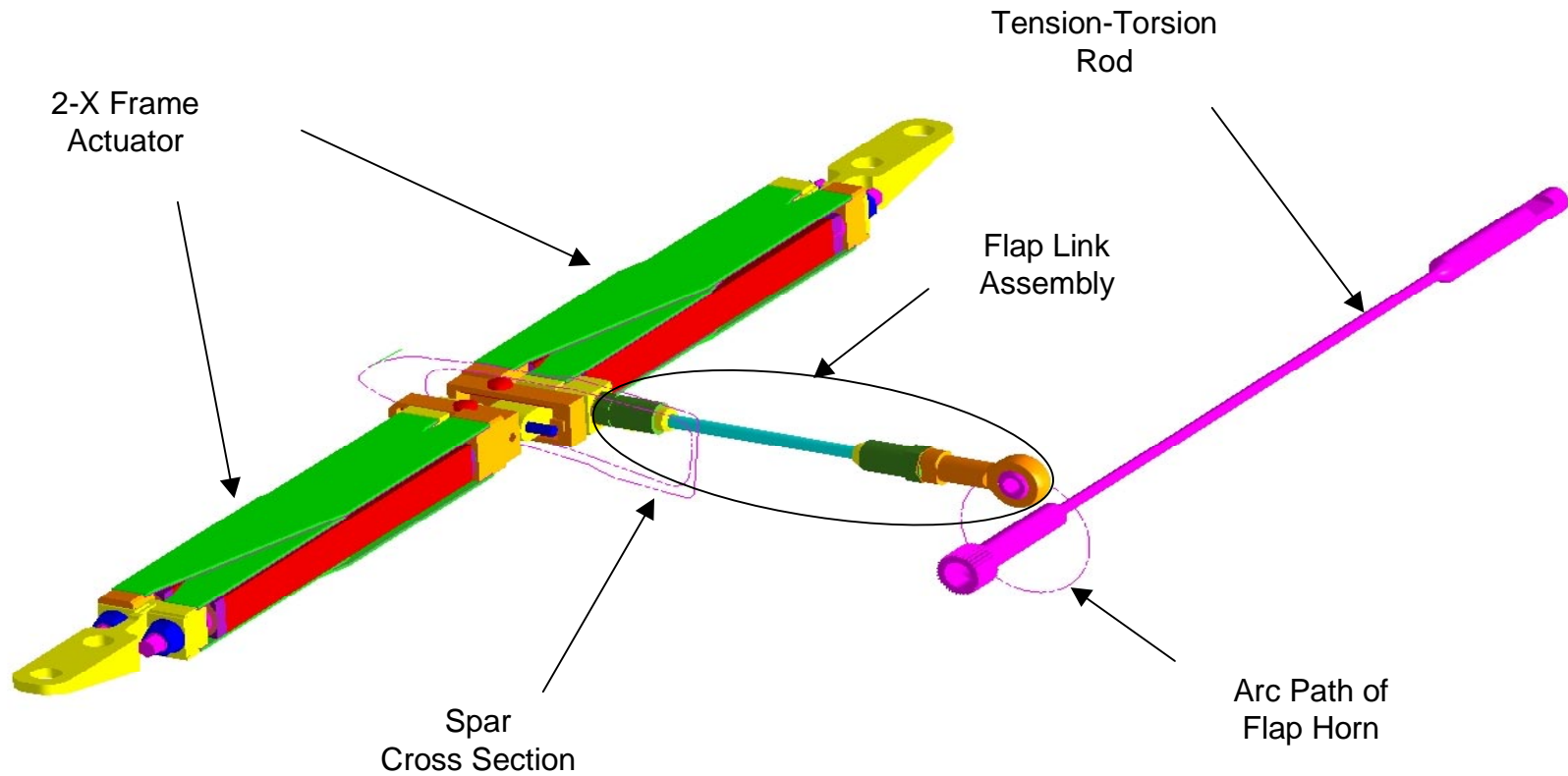
- Use custom PI HV stacks

Started development of switching amplifier



# ACTUATOR, FLAP LINK, TENSION-TORSION ROD

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# STRUCTURAL COMPONENT TESTING

## Flap link rod end bearing

- Simulated flap motion, 50 lb radial load
- 3 specimen, up to 45M cycles at 40Hz
- Breakout torque ~3in-lb; radial play <6mil

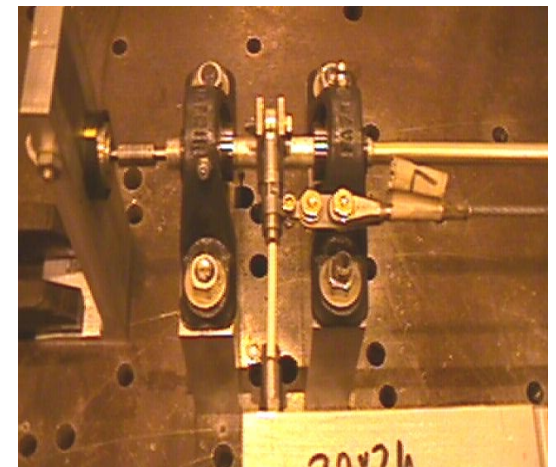


## Flap link flexure - fiberglass rod & attachments

- Compression test, tension test to failure

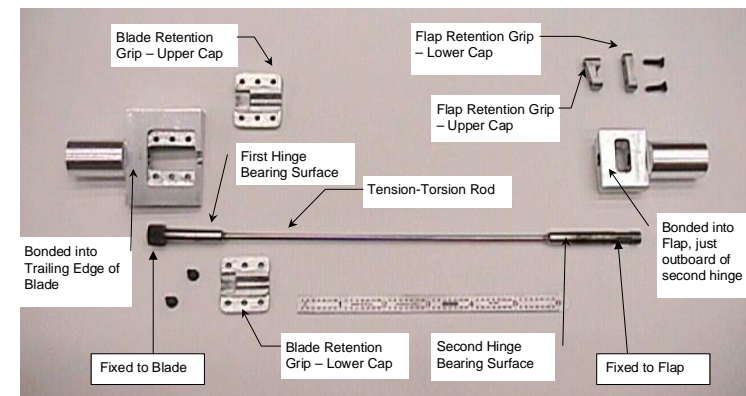
## Flap link endurance test

- Simulated flap motions and loads at 40 Hz
- CF effects: link shear load, t-t rod stretch
- 35M cycles; rod end radial play ~1mil



## Tension-torsion rod test

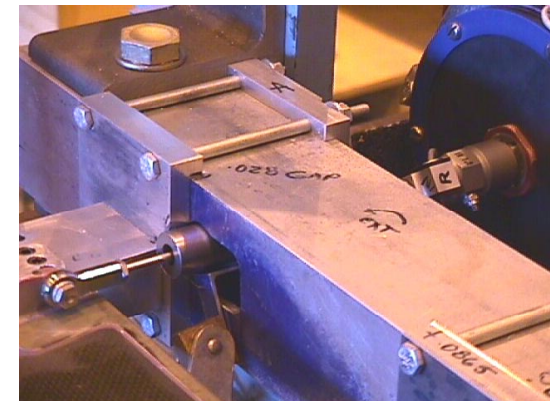
- 10k GAG cycles (ground-air-ground)
  - Combined axial and torsional loading
  - 108% RPM CF and torsional preload
- Static ultimate test
  - peak torsion load, axial load to failure



Structural and performance requirements met

## FULL SPAN FLAP -- TESTING

- Pitch stiffness test - dynamic (5Hz)
  - due to blade flap and flap/chord bending
  - level flt and maneuver conditions
- Frequency sweeps - 0 to 100Hz
  - baseline - up to 100 Hz
  - flap and flap/chord bending - up to 40 Hz
- Pitch stiffness test under CF loading
  - CF=0,250,500 lb; w/o bending deformation
  - static and dynamic loading
- Endurance testing
  - oscillate flap +/-4 deg at 25 Hz for 1M cycles
  - flap/chord deflection for high speed level flight
- Load levels comparable to static test
- No flap resonances observed
- Minor flap bearing wear, flap/rod galling at STA 159

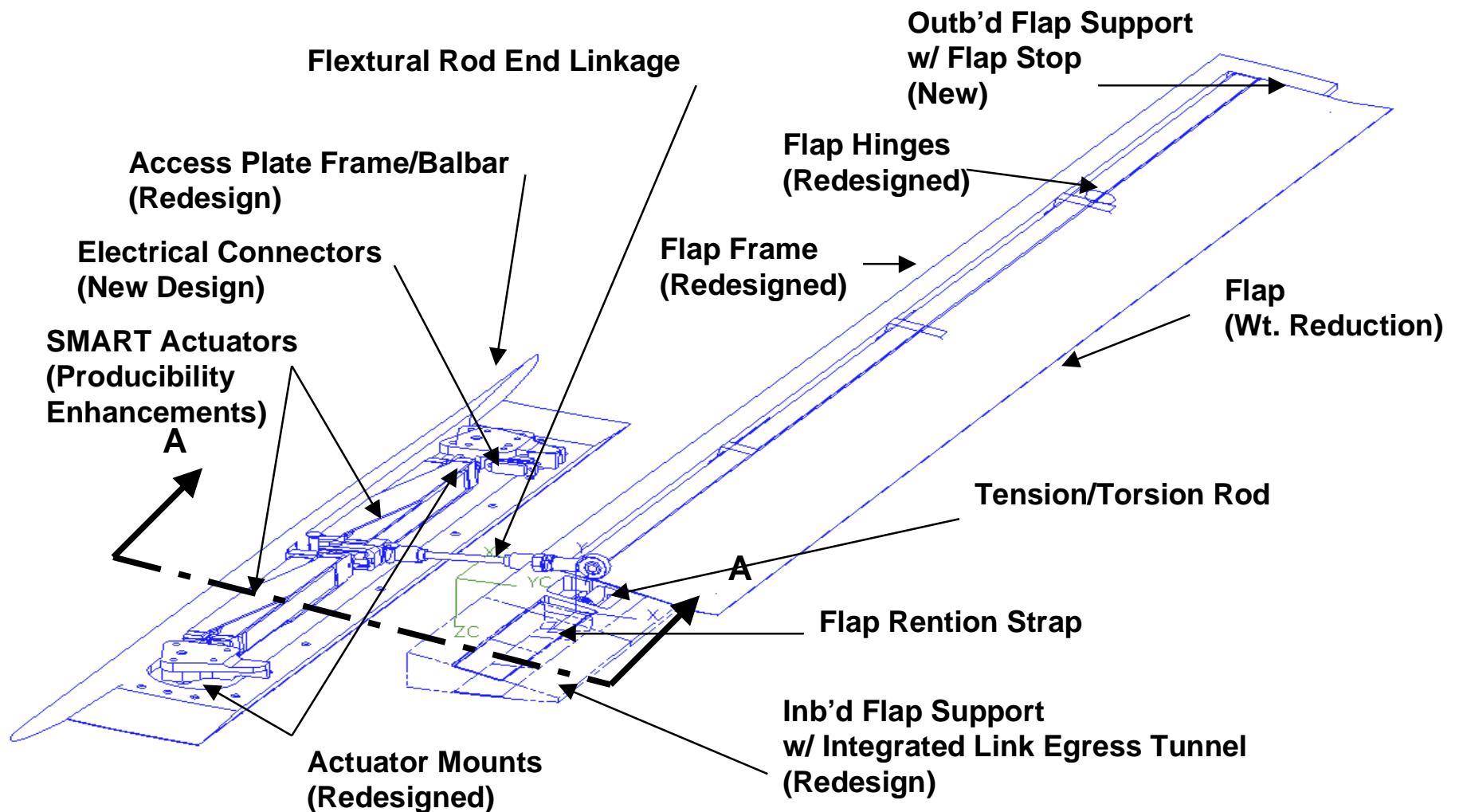


## **BLADE, FLAP, ACTUATOR DESIGN INTEGRATION**

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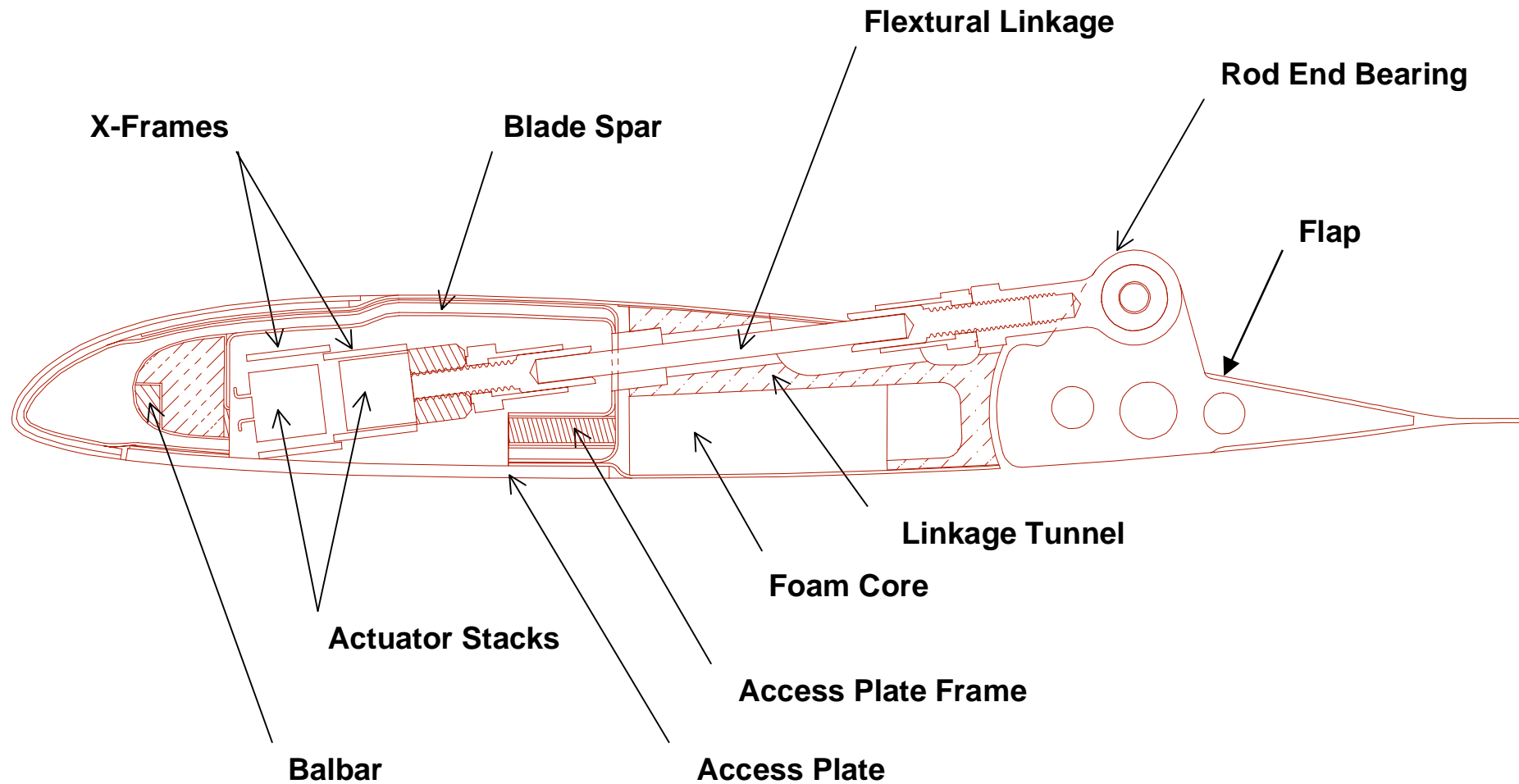
- **Actuator:** producibility, maintainability enhancements
- **Flap link redesign:** glas rod flexure w rod end bearing
- **Flap:**
  - optimized design - torsional stiffness, tension-shear coupling, weight
  - composite leading edge w integral LE weight, mass balance method
  - flap stop, CF strap
- **Actuator integration:**
  - mounts, isolation, debris retention, mid support,
  - preload adjustment, travel stops, electrical connectors
  - adjustment, maintenance provisions
- **Blade:**
  - weight reduction, material replacement,
  - actuator access cover and frame
  - actuator wiring, instrumentation integration,
  - flap support frame, flap hinge supports,
  - integral flap inboard support/link egress hole reinforcement
- **Tool proof blade and flap**
  - Tooling design and fabrication near completion
  - Blade and flap fabrication started

# BLADE, FLAP, ACTUATOR DESIGN INTEGRATION



# BLADE, FLAP, ACTUATOR DESIGN INTEGRATION

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# SMART ROTOR BLADE SKIN/CORE ASSEMBLY FABRICATION



**Upper Blade Skin**

36 " Flap Cove  
Skin Contour and  
1st Side Core Contour  
Mods. Completed



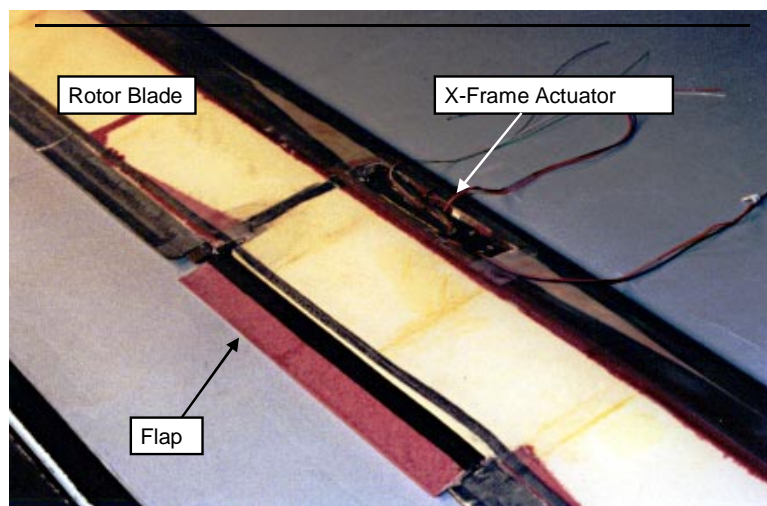
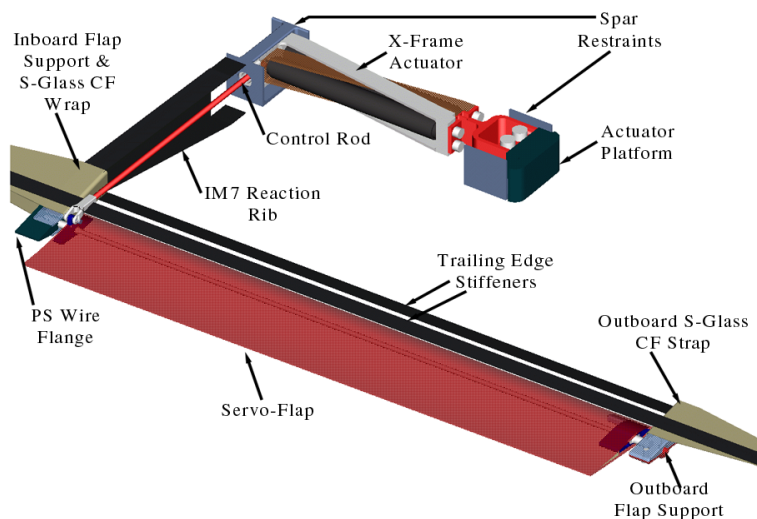
**Upper Blade Skin/Core Assy. Bonded**

Upper Skin

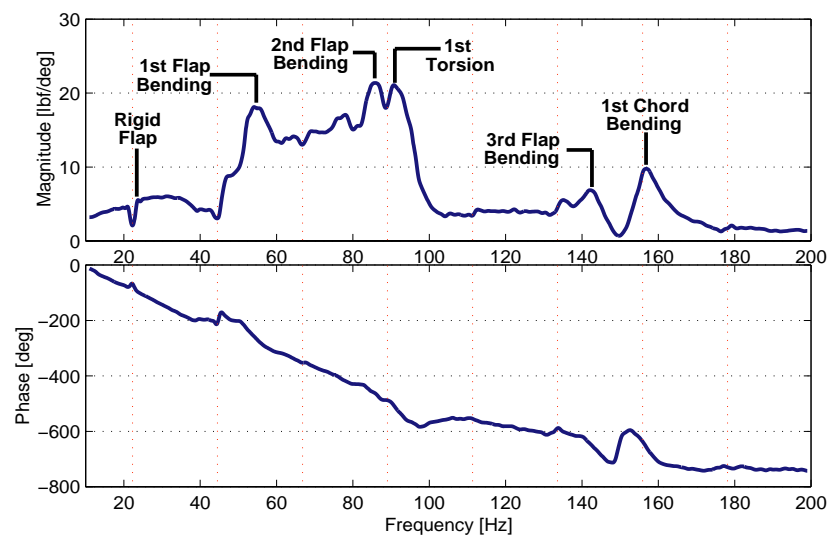
Core Bonding  
Completed

Skin/Core is ready for 2nd  
side machining

# 1/6 Scale CH-47 Active Flap Hover Test

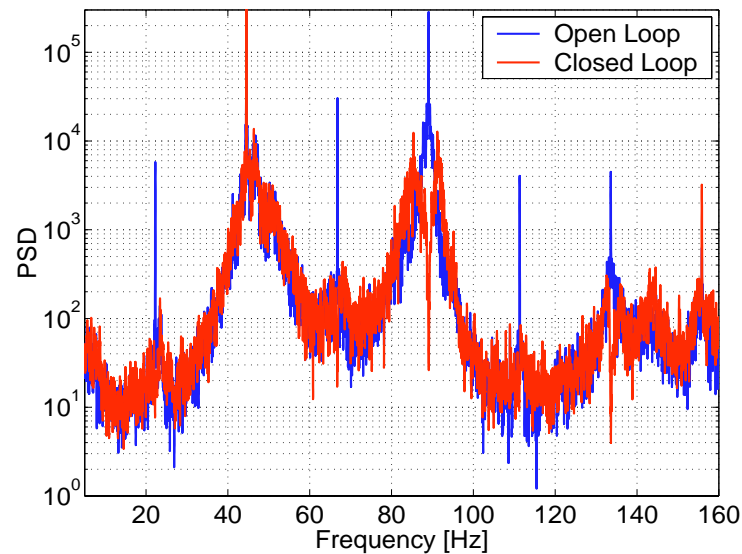
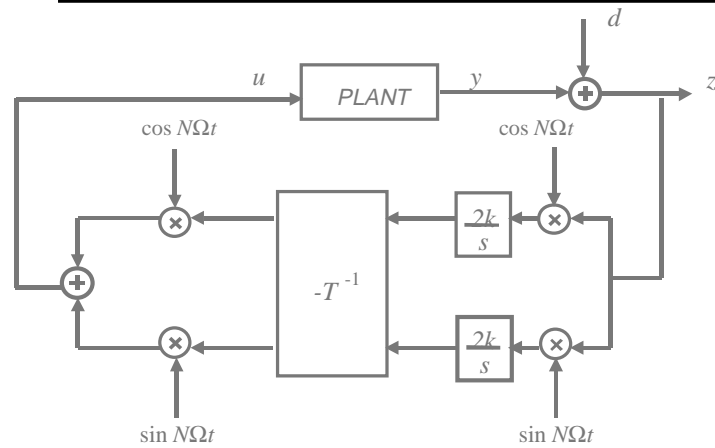


## Flap Effectiveness in Controlling Hub Thrust

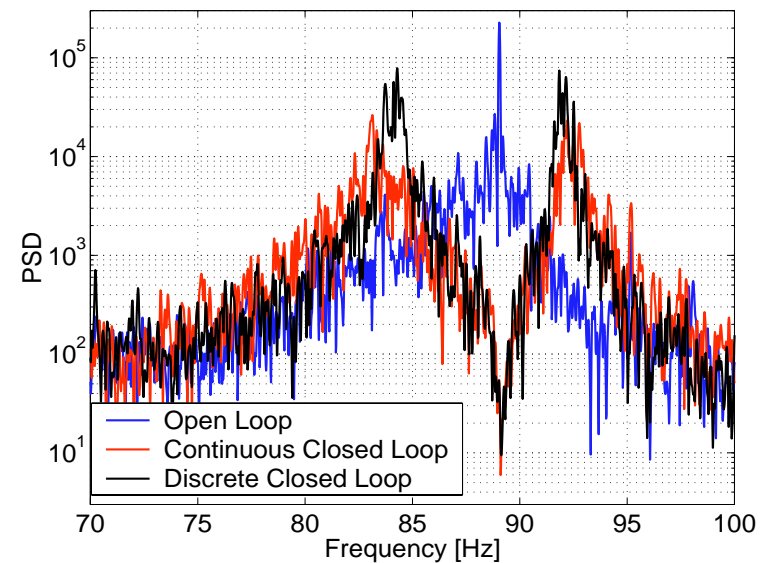


*Scaling to CH-47D, 6 active blades, 60 V/mil P-P field, yields 16,000 lbf P-P actuation at 3/rev - 32% of aircraft's gross weight*

# Continuous Time Higher Harmonic Control (HHC) of Hub Thrust



Continuous and discrete controllers at 4/rev  
Using identical T matrices



Combined Frequency Control: 1, 3, 4, 5, 6/rev  
2/rev control difficult due to zero in response

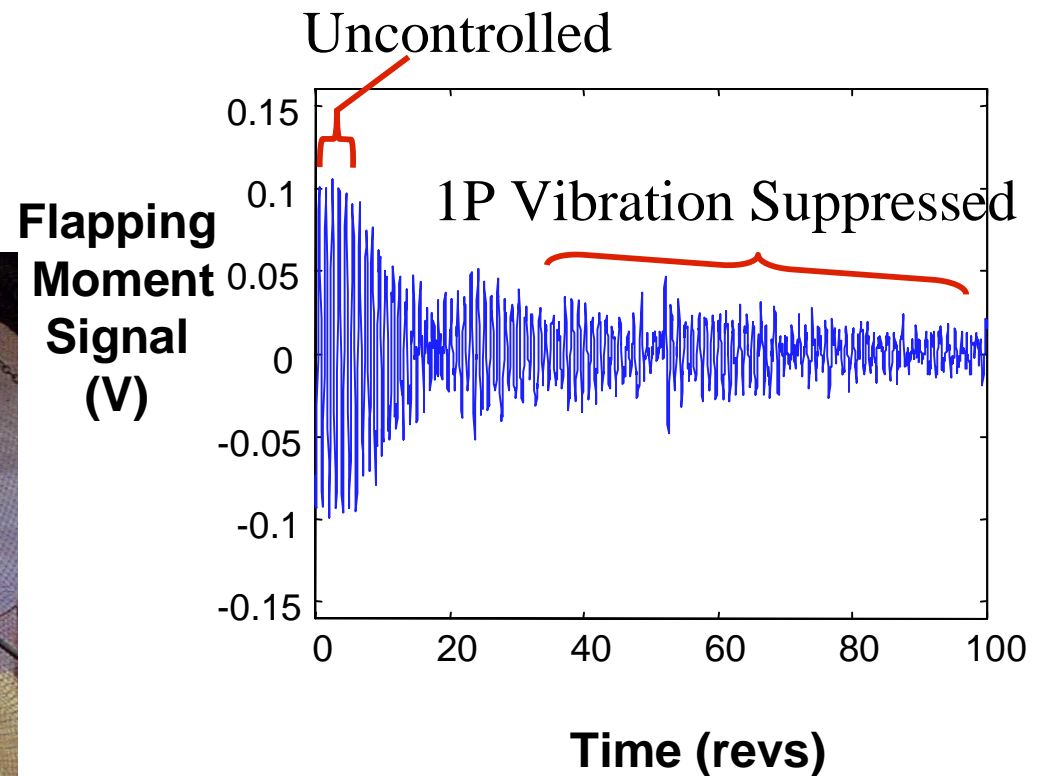
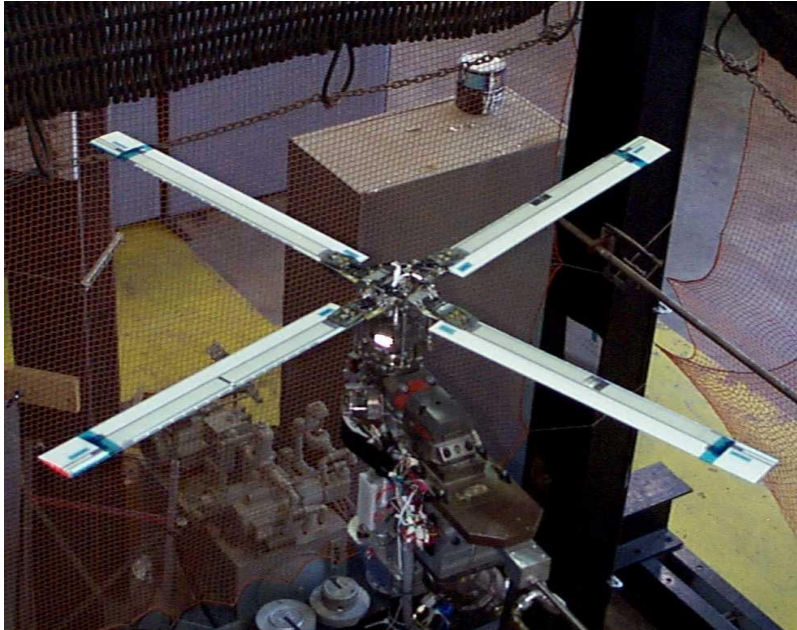
# Neural Network Control - NNC

## Realtime Closed Loop Tests in Hover



### Piezo-actuated Smart Active Blade Tip rotor

- Vibration control of flapping moment on a single Mach-scaled blade
- 2000 RPM



# Neural Network Control

## Real Time Closed Loop Tests in Forward Flight

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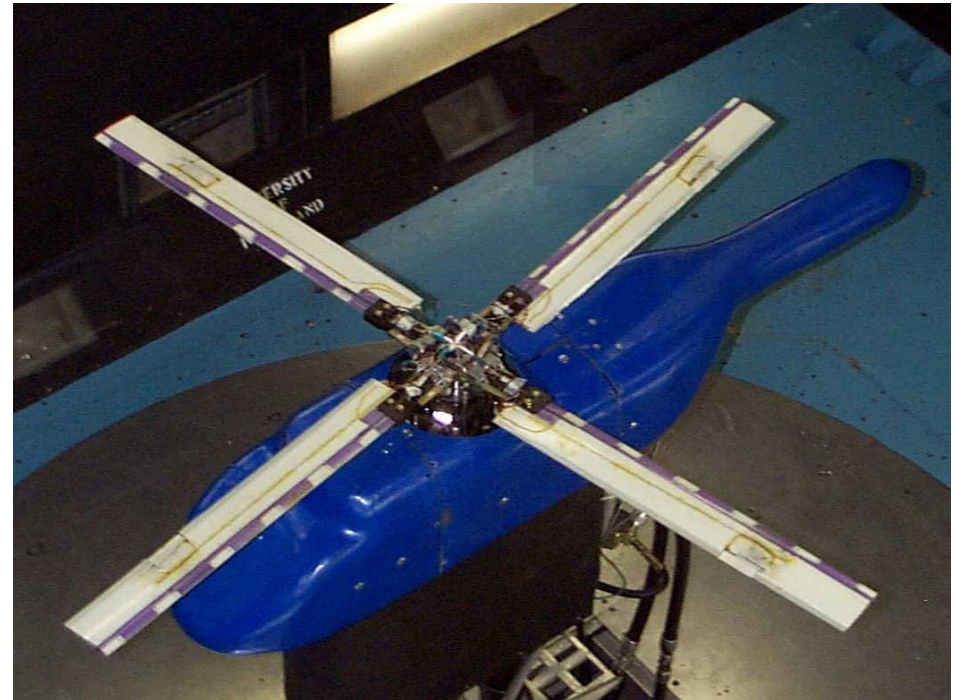
### Piezobimorph Actuated Trailing-Edge Flap (Mach scale)

First entry - Glenn Martin Wind Tunnel

- 4-bladed rotor with dia. 6 ft
- Vibration reduction of flapping moment (90%) and fixed frame thrust (40%) by a single rotor blade with an active trailing edge flap
- Rotor speed 1000 & 1500 RPM
- Wind speed 27 - 80 mph

Second entry plans

- Actuate all flaps, control 5 hub loads
- Expand envelope; 2000rpm, 160mph



# SMART ROTOR PROGRAM TASK 1 -- ACCOMPLISHMENTS

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## **Actuation System Development**

- **Completed bench testing of single-x actuator with TRS high voltage stacks**
- **Design of 15% growth actuator; 1-x prototype fabrication; strength test to failure**
- **Completed modeling and structural/performance analysis**
- **Reassembled 2-x frame actuator with PI stacks; started controls development testing**
- **Selected and ordered piezo stacks for tool proof actuator; started fabrication**

## **Blade/Actuator Design Integration**

- **Fabricated/tested rod end bearing, flexure - glass rod/attachments, flap link, t-t rod**
- **Modeling and structural analysis of blade/flap/actuator section - 3D FEM**
- **Aeroelastic rotor modeling, analysis; dynamics, loads, stability**
- **Completed blade, flap, actuator design integration - required changes**

## **Fabrication, Test**

- **Started tool and fixtures design, modification, N/C programming and fabrication**
- **Started tool proof blade fabrication; blade skins, core, flap skins, details**
- **Started test stand and rotor refurbishment**

# **SMART ROTOR PROGRAM TASK 1 -- ACCOMPLISHMENTS, ctd**

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## **UCLA**

- **Performance of piezo stacks from TRS and RSC/KC (custom) and PI (HV, COTS)**
- **Investigated effect of temperature on strain output and current requirements**
- **Fatigue tests of stacks from PI (low and high voltage) Sumitomo, TRS and RSC**

## **MIT:**

- **Documented results from the 1/6 scale CH-47 active flap rotor test**
- **Compared higher harmonic control (HHC) and neural network control (NNC)**
- **Development of the continuous time control HHC algorithm was continued**
  - **control strategies; system ID concepts for forward flight; phase lock loop**

## **UM:**

- **Demonstrated NNC algorithm real time on a two smart material Mach scale rotors**
  - **Active tip twist rotor in hover: suppressed vibratory blade flapping moments at 1P while introducing specified moments at other harmonics**
  - **Trailing edge flap rotor in wind tunnel, at speeds up to 70 knots: suppressed vibratory blade flapping moments at 1P and vibratory thrust at 4P**
- **Enhanced UMARC trailing edge flap model by adding aerodynamic balance and airfoil table lookup. Performed numerical simulations to investigate the effects of flap spanwise location and actuator stiffness.**

# SMART ROTOR PROGRAM TASK 1 -- SUMMARY

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## Lessons Learned

- Piezo stack quality and endurance remain key issue; PI - quality, RSC - performance
- Growth actuator with high voltage stack exceeds requirements (projected 3 deg w RSC)
- Blade design integration challenges overcome; required design changes incorporated
- Started fabrication of full scale hardware; good interaction w production shop
- Continuous time HHC and NNC offer improved performance vs basic HHC
- Demonstrated NNC on active flap rotor in hover and forward flight; flapping, thrust

## Summary

- Design completed; full scale hardware fabrication started
- Integrated system, whirl tower, MD900 flight tests to be completed
- Expect 80% vibration, 10dB BVI noise reduction; improved range, maneuverability

## Opportunities

- Additional flight testing
- NASA Ames 40x80 foot wind tunnel entry

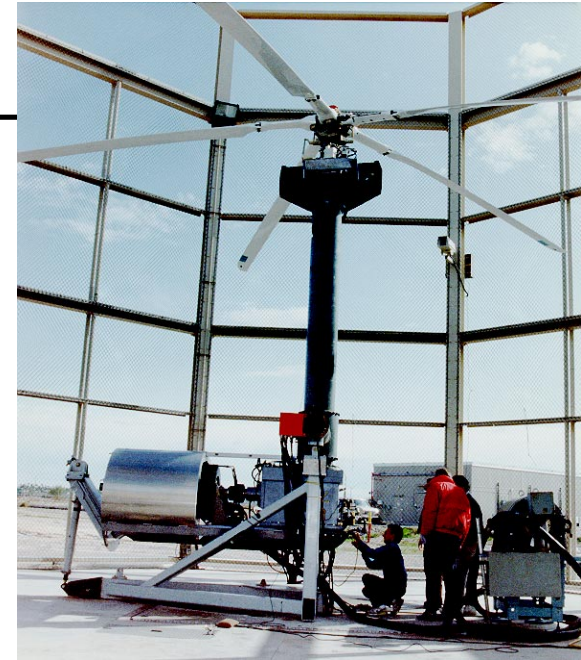
# SMART ROTOR DEMONSTRATION PHASE II PROGRAM

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## Task 1: MD900 Active Flap Rotor Flight Test

**Objective:** Demonstrate performance, cost benefits

- Piezo actuator development, blade design integration
- Integration test: blade, flap, actuator, amplifier, 3Q00
- Fabricate actuation system and rotor blades, 4Q00
- Whirl tower test, 1Q01; MD900 flight test, 2Q01
- NASA Ames 40x80 wind tunnel test, unfunded



# DARPA SMSDC Task II- 1/6-Scale CH-47 Active Materials Rotor (AMR)

June 26, 2000  
TECHNICAL  
INTERCHANGE

**BOEING**

**Bob Derham**  
**(610) 591-5919**

**MIT**

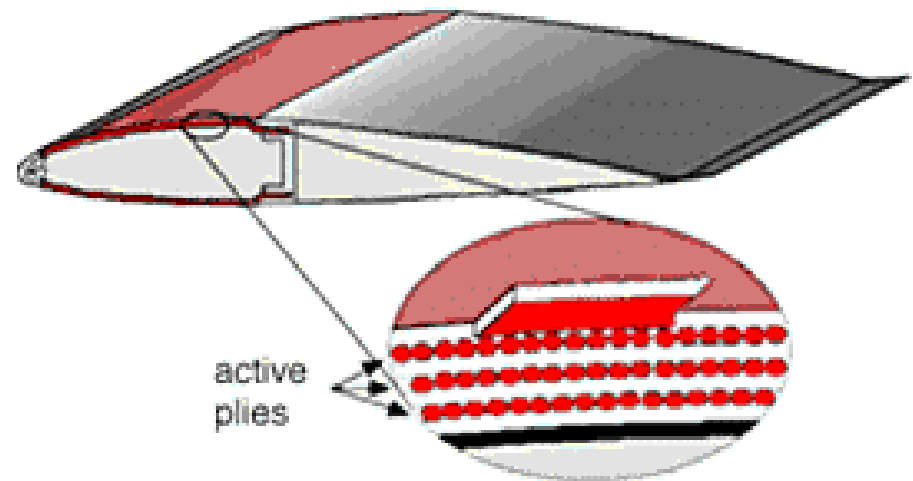
**Nesbitt Hagood**  
**(617) 253-2738**



# Integral Twist - Concept

SMSDC

- Incorporate Active Fiber Composite (AFC) plies within composite blade for twist actuation
  - Distributed actuators integrated within composite spar
  - Anisotropic actuation at  $\pm 45^\circ$  induces shear stresses
- Advantages:
  - Distributed actuation (redundancy)
  - Large bandwidth (kHz)
  - High internal energy density
  - Structural integrity
  - No articulating components
  - No extra profile drag
  - Multiple control degrees of freedom (twist, bend, distribution)



## Task 2 -



# Active Materials Rotor (AMR)

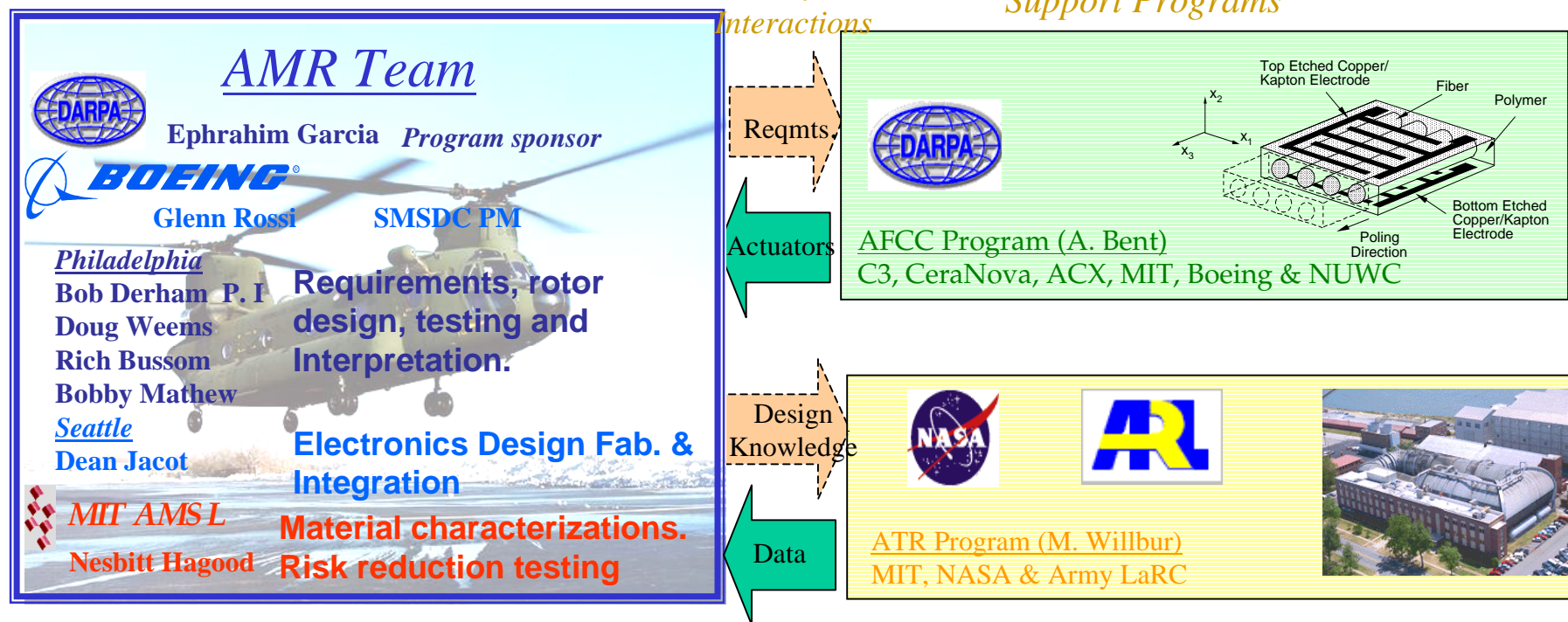
**SMSDC**

**Task 2 Objective** - Design, build and test a scaled model of an advanced Chinook rotor using active materials. The expected outcome will be improved rotor and vehicle performance, while initiating the process for qualifying active fiber composites (AFC's) for aerospace applications.

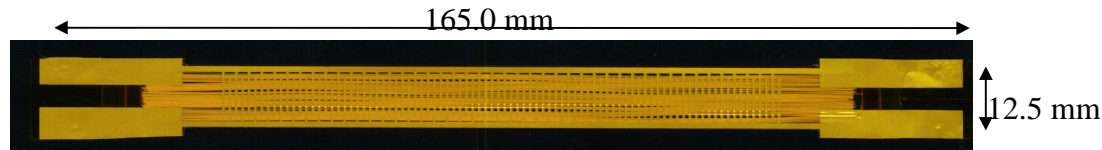
**The only program conducting mechanical characterizations of AFC's for morphing (adaptive) structures**

Key

Support Programs



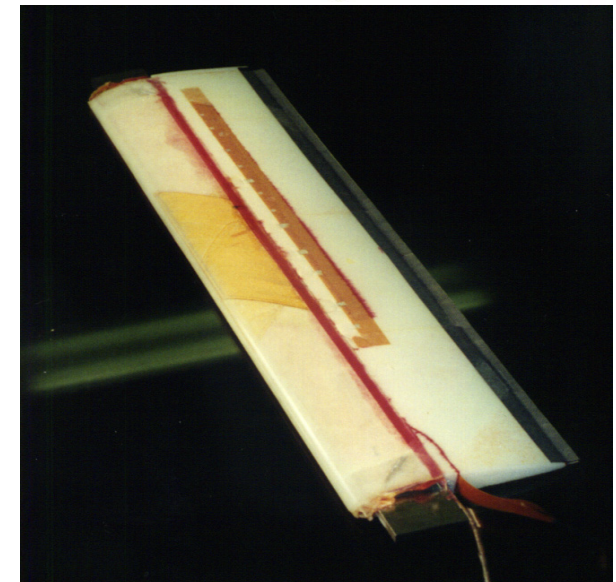
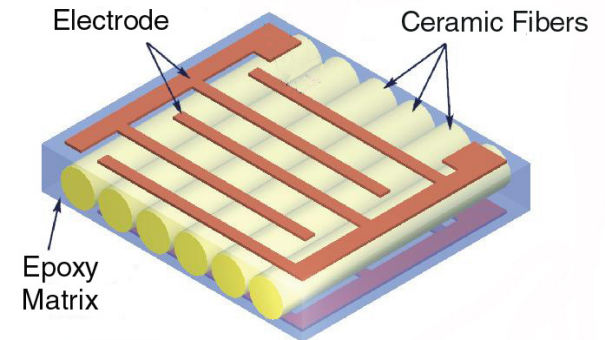
# Risk Mitigation Completed



Characterization Test Coupon

## Initial Characterization (for WT testing):

- Defined new (lower) voltage cycle through improved authority and innovative blade design
- Defined 3rd generation active blade design (more robust electrical connections, new power bus, advanced switching electronics, state-of-the-art planform, dynamically representative tuning, representative survivability/loads)
- Improved Strain Performance for nominal rep cycle
- Non-linear stress-strain behavior measured and several rotor blade sections bench tested.
- Qualified for WT electrical fatigue.



MIT/Boeing AMR "Section 4"

# Understanding New Design Space for an Active Materials Rotor

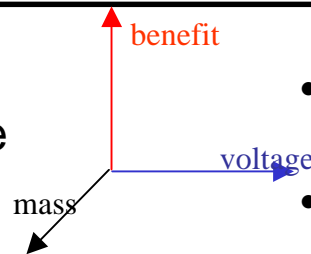
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Goal of Pre-Design is to gain understanding for design space and sensitivities:

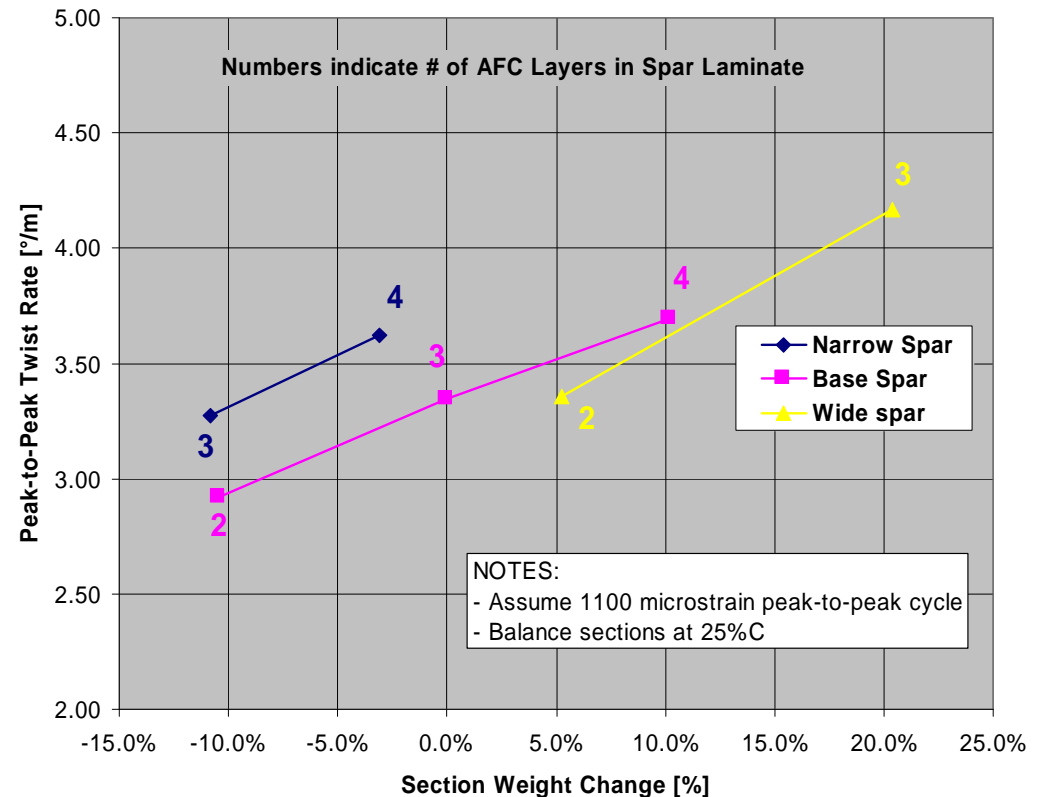
1. Want to minimize voltage
2. Want to minimize c.f. (mass)
3. Want to maximize benefit (twist)

Parameters Examined to date:

- spar size (active & passive)
- number of active plies
- actuation schedule
- blade geometry (thickness/airfoil)
- blade planform
- passive ply orientation (GJ)
- CG balance strategy
- actuator placement (spanwise)
- actuator orientation



- C.G. is not as much of a limitation as we thought (for distributed actuators)
- Reducing GJ is not as much of a benefit as we thought





# Nothing Changed from Last Year to This Except -



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## Blade Planform

- 2nd Generation Helo Rotor to 3rd Generation Helo Rotor
  - Latest airfoils
  - Swept Tip
  - Non-linear twist
- Motivated by :
  - better vehicle performance
  - capture transition opportunities
  - desire to be on the leading edge
- Risks:
  - Very innovative (different) design
  - No full-scale existing comparator

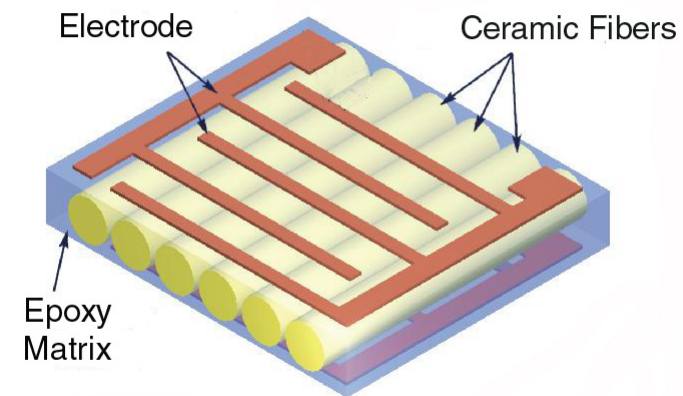
## Actuator

- 2nd Generation AFC to 3rd Generation AFC
- Motivated by :
  - Better quality/consistency
  - Less costly (cheaper system)
  - Desire to be on leading edge (step towards scale-up)
  - Better mass efficiency
  - Easier manufacture (less electrical connections)
- Risks :
  - 1st application for this system (not a lot of data)

# Actuator Evolution

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- 1st Generation
  - Cu Ka (1mm); Shell high Viscosity ;  
Narrow Diameter, ~ 80% V.F.
  - Prototype manufacturing, Phase 1  
Connections
  - ~650 (best) ms/3KV
- 2nd Generation
  - Ag-Ink (1mm); Aerospace grade film;  
Narrow Diameter, ~80% V.F.
  - Small-scale production, Phase 1  
Connections
  - ~1000 (avg.) ms/3KV



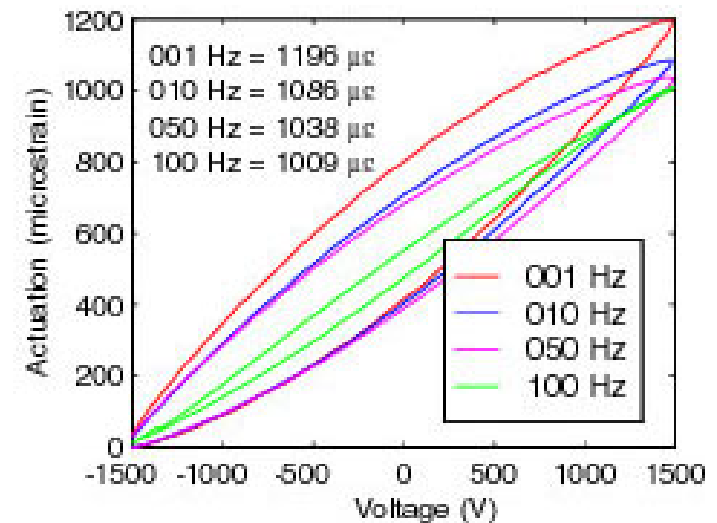
- 3rd Generation
  - **Ag-Ink (1mm); Aerospace grade film;  
2x Diameter, ~90% L.F.**
  - **Large-scale production, Phase 2  
Connections**
  - **~1200 (avg.) ms/3KV**

# Summary and Future Characterization Work

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## Summary

- Switched to “large fiber” AFC material system
  - Average actuation = 1200 $\mu\epsilon$  for 3kVpp at 1 Hz
  - Depolarization voltage limit < -2000V
- $E_{33}$  design modulus for large fiber active ply measurements underway
- Performance under tensile loads similar to small fiber AFC system
- No Electrical fatigue expected to 20M cycles @ 3kVpp (0 DC offset)



Large Fiber AFC Actuator  
Unlaminated

## Future work

- Complete characterization test matrix for large fiber AFC actuators
- Develop testing methods to determine survivability and performance under combined electromechanical loads
- Characterize next generation AFC's (25% greater authority for constant mass, 50% for constant volume).

# Planform Evolution

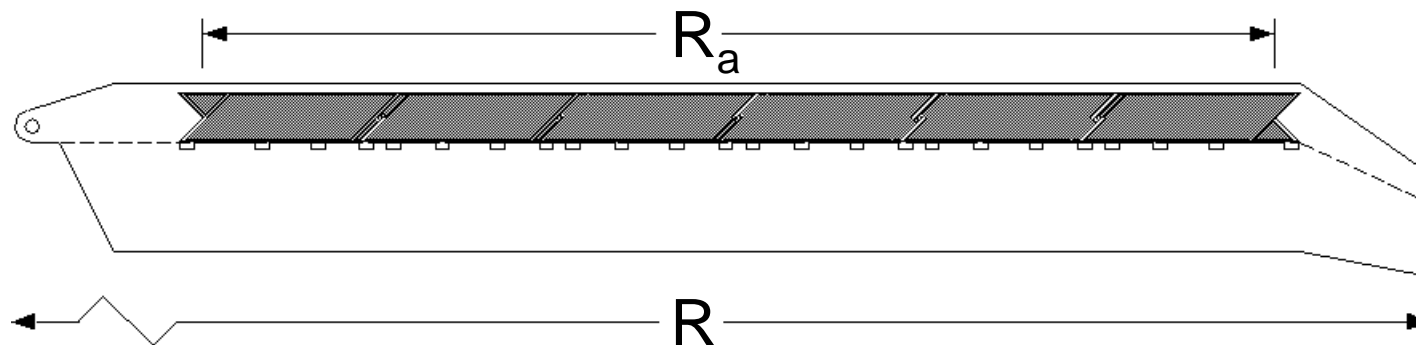
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## Began with CH-47D

- 12% t/c, older airfoils, straight, linear twist
- Desire to relate to known design and something flying

## Evolved to Advanced CH-47X

- 10% t/c, newest airfoils, swept, non-linear twist
- Higher solidity (more lifting capability at faster speeds)
- Desire to show relevance and value to Boeing and DOD (JTR/FTR)
- Greater transition opportunities
- Closer to full-scale demo (next generation rotor)



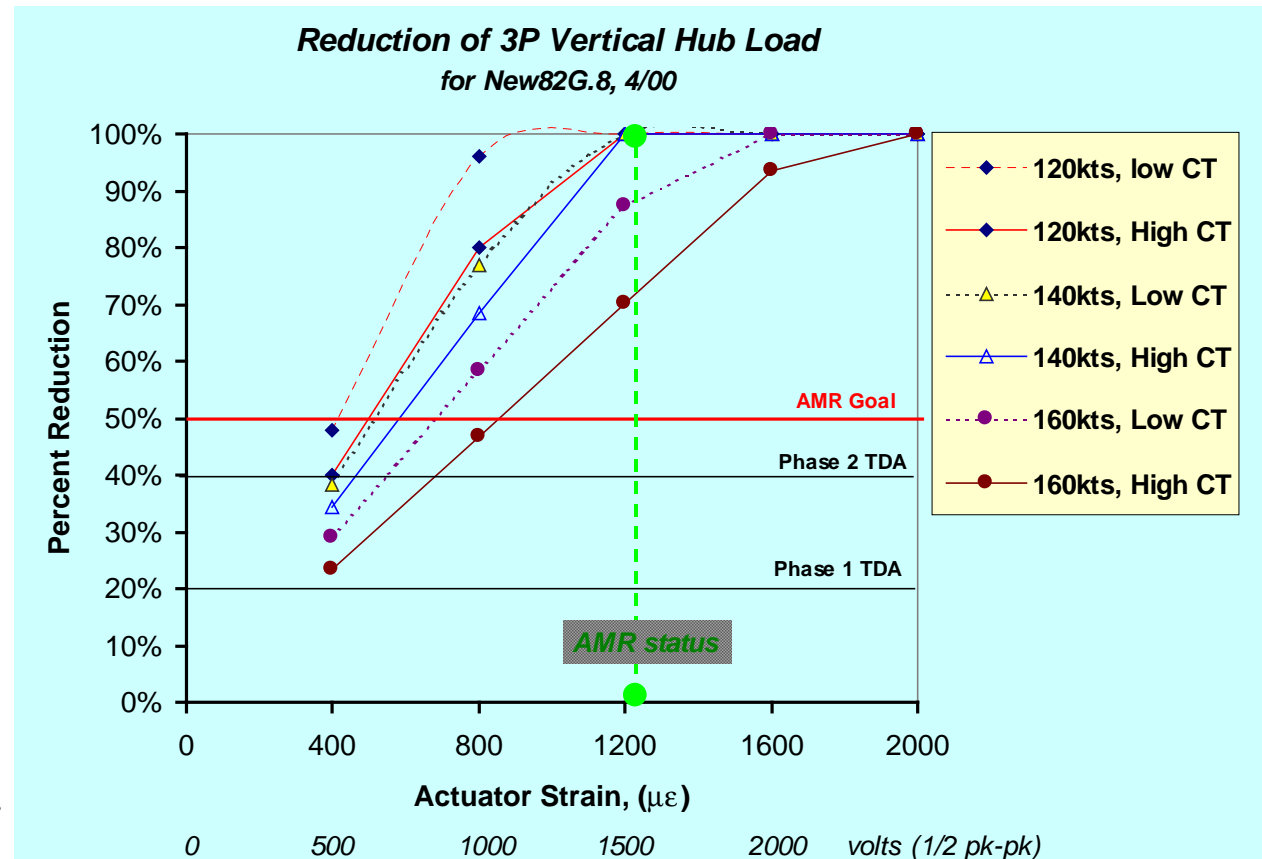
# Preliminary Design Requirements & Goals

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Our program goal (internal) for 50% reduction exceeds TDA Phase 1 & 2 goals

Current actuator meets requirements at spec. voltage cycle, greater actuation authority can be used to lower voltage

3-bladed rotors are especially challenging and AMR benefits show greater promise than other passive (or active) techniques



**Design Meets or Exceeds Army TDA & AMR Goals**



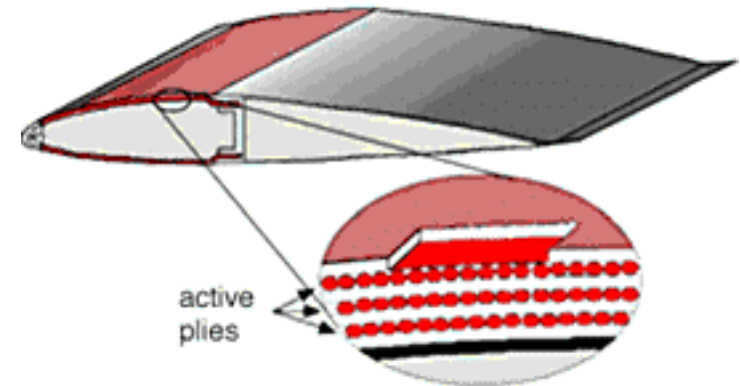
# Integral Twist -



## Accomplishing Our Goals

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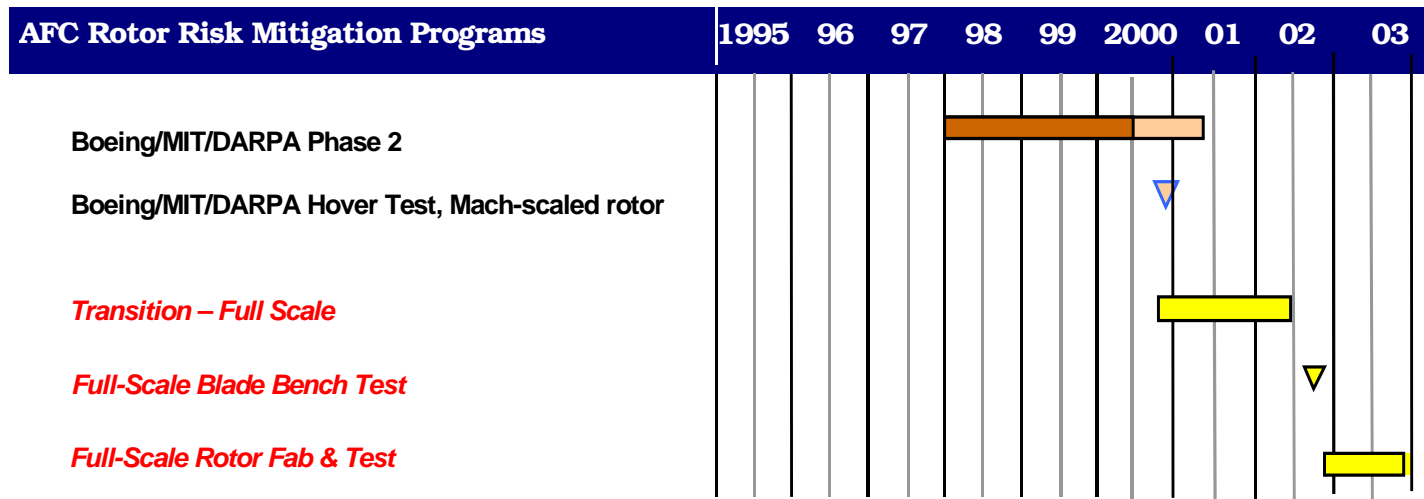
- Better, cheaper has (and is) happening
  - 25% greater authority (on a mass basis) available today , 50% greater authority (on a volumetric basis) at same price.
- Industry experience has helped with “buy-in”
  - Task 2 is only Program (or customer) looking at mechanical integration issues and properties of adaptive (moving) AFC structures
  - Defined material selection criteria, test procedures, qualification standards and achieved good understanding of limitations and issues.
  - Voltage design space has been revised (peak is coming down)
- Promises Kept:
  - Distributed actuation (redundancy)
  - Large bandwidth (kHz)
  - Structural integrity
  - No articulating components
  - No extra profile drag





# Upcoming Milestones

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## NEAR TERM

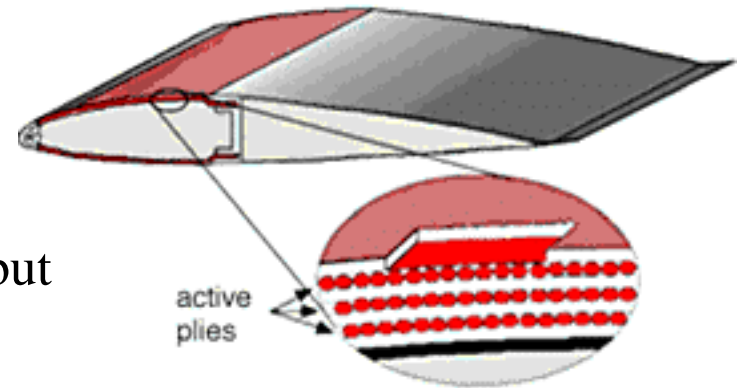
- August 2000 - Process Blade (tool prover)
- Oct. 2000 - Blade(s) Complete
- Dec. 2000 - Hover Test

# Integral Twist - Longer Term Issues



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- Actuators characterization needs to mature
  - Promise of vastly reduced costs
  - Advancement of material outstripping our ability to characterize it.
  - Current AFC appropriate for smaller rotors, but needs to be scaled for growth Chinook rotor
- Electronics Still an Issue
  - Voltage Requirements have come down, but electronics need more development (miniaturization, qualification, etc.)
- Need to quantify benefits more precisely
  - FWD. Flight WT test is 1st (and important) step (uniformity and closed loop control)
  - Cruise L/D and Hover benefits are unknown unknowns
- We need (and are ready for) full-scale.



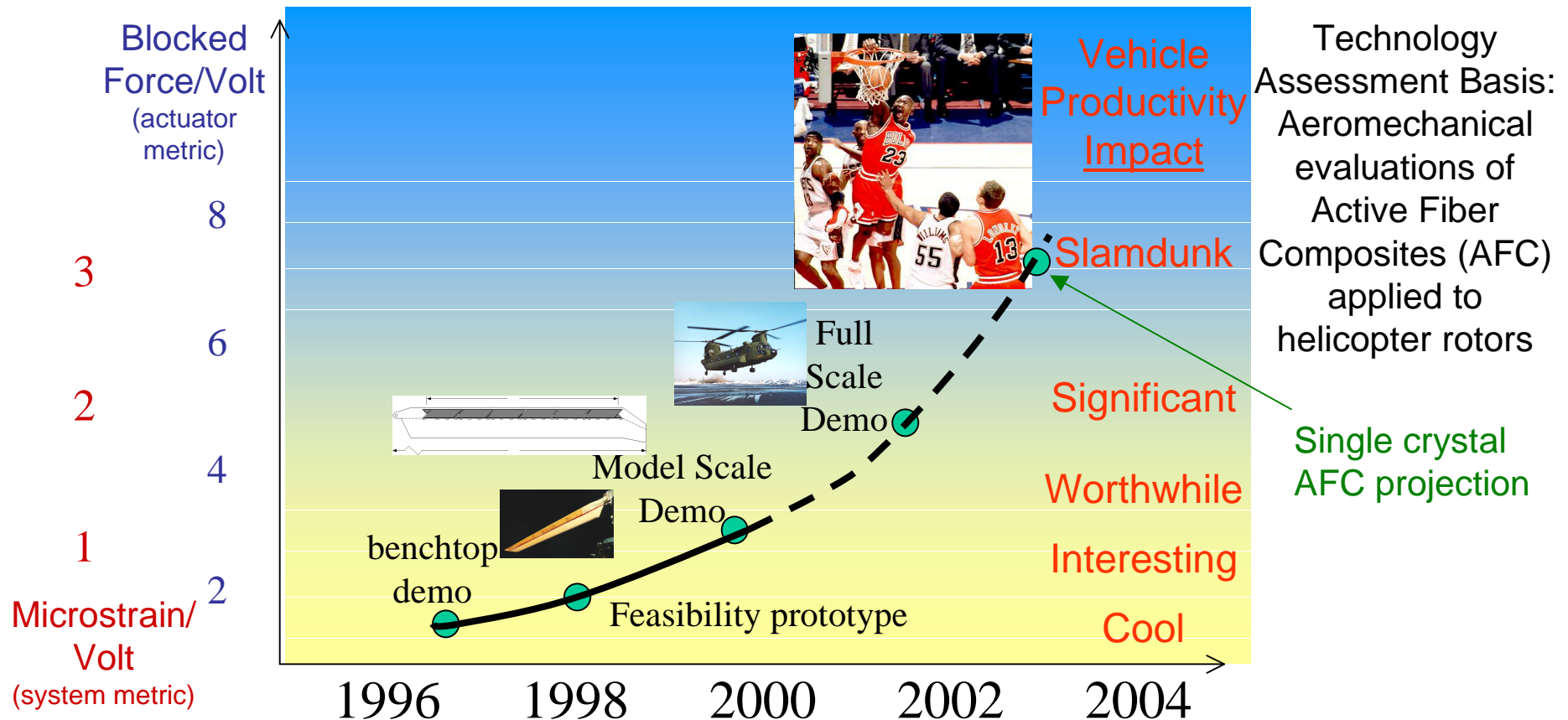


# Application to Helicopters -

Where We've Been and Where We Need To Go



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$$\text{Vehicle Productivity} = f \{ K [ \odot \text{Payload} \times ( \odot \text{Speed} + \odot \text{Range} ) ] / C [ \odot \text{OC} + \odot \text{IC} ] \}$$

Factors: aeromechanical efficiency, existing equipmen., direct weight, system weight, system drag

operating cost + initial cost